Experimental and Theoretical Studies of Ice-Albedo Feedback Processes in the Arctic Basin

Gary A. Maykut
Department of Atmospheric Sciences
University of Washington
Seattle, Washington 98195-1640
Voice: 206-543-0164 FAX: 206-543-0308
maykut@atmos.washington.edu

Thomas C. Grenfell
Department of Atmospheric Sciences
University of Washington
Seattle, Washington 98195-1640
Voice: 206-543-9411 FAX: 206-543-0308
tcg@atmos.washington.edu

Award Number: N000149710765

LONG TERM GOALS

Our overall goal is to develop a quantitative understanding of processes that collectively make up the *ice-albedo feedback mechanism*. This mechanism is generally believed to be a key factor in amplifying natural variations within the earth's climate system. Central to achieving this understanding is learning more about how shortwave radiation is absorbed and distributed in the ice pack and upper ocean, and how this distribution affects the regional heat and mass balance of the ice cover. Complicating the problem are a variety of issues related to the extreme sub-grid scale variability of the Arctic ice cover and to how such variability can be accounted for in large-scale models. Our long-term goal is to develop accurate formulations of major ice-albedo feedback processes in a form suitable for inclusion in climate and general circulation models.

OBJECTIVES

We are investigating a variety of specific problems related to the interaction of shortwave radiation with the ice and ocean. Of particular interest are factors that affect the amount of light transmitted to the ocean through the ice cover. Overall, the research addresses the following general questions: (1) How is shortwave radiation that enters the ice-ocean system partitioned between reflection, surface melting, internal heat storage, and transmission to the ocean, and how is this partitioning affected by the physical properties of the ice, snow cover, melt ponds and distribution of contaminants? (2) What is the areal distribution of ice, ponds and leads in perennially ice-covered regions; how does this distribution vary with time; and how does it affect area-averaged heat and mass fluxes? (3) What are the crucial variables needed to characterize ice-albedo feedback processes and their effect on the heat and mass balance of the ice pack, and how accurately can they be treated through simplified models and parameterizations?

APPROACH

These issues are being addressed through a combination of field measurements, laboratory observations and theoretical modeling. Field data in support of this work were collected over a complete annual cycle at the SHEBA Drift Station in the Central Beaufort Sea. Measurements were carried out jointly with D.K. Perovich and colleagues from the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) and focused on: (1) documenting the temporal evolution and spatial variability of albedo, absorption and storage of solar energy by the ice, light transmission to the ocean,

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2002**	2. REPORT TYPE	3. DATES COVERED **00-00-2002 to 00-00-2002**

4. TITLE AND SUBTITLE
Experimental and Theoretical Studies of Ice-Albedo Feedback Processes in the Arctic Basin

5a. CONTRACT NUMBER
5b. GRANT NUMBER
5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER
5e. TASK NUMBER
5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Department of Atmospheric Sciences,,University of Washington,,Seattle,,WA, 98195

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Our overall goal is to develop a quantitative understanding of processes that collectively make up the ice-albedo feedback mechanism. This mechanism is generally believed to be a key factor in amplifying natural variations within the earth???s climate system. Central to achieving this understanding is learning more about how shortwave radiation is absorbed and distributed in the ice pack and upper ocean, and how this distribution affects the regional heat and mass balance of the ice cover. Complicating the problem are a variety of issues related to the extreme sub-grid scale variability of the Arctic ice cover and to how such variability can be accounted for in large-scale models. Our long-term goal is to develop accurate formulations of major ice-albedo feedback processes in a form suitable for inclusion in climate and general circulation models.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**7**	

pond coverage, and mass changes in various types of sea ice, (2) soot loading of the snow to determine whether contaminants generated by the ship might alter the normal albedo and melt cycle, and (3) ground-based and aerial ice surveys to obtain a statistical picture of spatial variability and fractional area covered by individual ice types within the SHEBA region. Such data are needed to estimate the regional input of shortwave energy to the ice and ocean, lateral melting on floe edges, and melt pond evolution, and to improve our understanding of ice-albedo feedback processes in the Central Arctic.

Complementing the field observations were an extensive series of structural and optical measurements carried out in laboratory sea ice samples under a wide range of temperatures (-2 to –34 °C). These data have been used to develop and test a model that relates structural and optical properties in sea ice. Such a model is needed to provide a general description of radiative transfer in sea ice and will form the basis for modeling efforts to predict the optical evolution of the ice cover during the summer melt season. Analysis and interpretation of the experimental data were made possible through development of a two-dimensional Monte Carlo model which allows us to investigate how horizontal variability affects radiative transfer in sea ice. The model is also being used in the analysis of vertical irradiance profiles collected in bore holes during the SHEBA Project.

WORK COMPLETED

Ongoing analysis of the SHEBA data has shown a surprisingly large amount of heat in the summer mixed layer, leading to total mass losses at the underside of the ice pack that were comparable to those at the upper surface. The origin of this heat appears to have been largely solar radiation transmitted through the ice pack. Since the amount of open water was relatively small, much of this energy must have been transmitted through the ice rather than through leads. Light extinction coefficients for sea ice measured during previous field experiments, however, are too large to explain the amount of heat observed in the water. Because heat transfer from the ocean appears to be a major factor in the SHEBA heat and mass balance, recent efforts have focused on trying to better understand and quantify shortwave transmission by the ice. In particular, we have been: (1) using irradiance profile data to estimate spatial and temporal variations in extinction coefficients, (2) looking at the two-dimensional nature of the radiation field near melt ponds, and (3) continuing to investigate relationships between the optical properties of the ice and its structure. These analyses have required application of both our 2-D Monte Carlo model and our structural-optical model which, in turn, has led to further improvement and refinement of these two models. In addition, we have continued to analyze other basic SHEBA heat and mass balance data which were discussed in detail in last year's Annual Report. Results from this work are being presented in eight journal papers which are either in press, submitted, or in preparation.

RESULTS

Monte Carlo Model

A two-dimensional Monte Carlo model of radiative transfer in sea ice, which we designed and constructed to analyze optical measurements from ice core samples, has been enhanced to treat both horizontal and vertical variability in refractive, cylindrical domains. This model uses a backwards Monte Carlo method that is computationally efficient and relatively fast. Vertical variability is treated using multiple horizontal layers, and horizontal variability with concentric vertical shells. Figure 1(a) illustrates the geometry of an example with 3 layers and one shell. The detector in this case is located beneath the sample, but can be placed anywhere within or on the sample. Photons can be released at

any angle from the detector and their trajectories monitored to obtain a solution to the radiative transfer equation at the site of the detector. As discussed in the following sections, this model also has direct practical applications in the analysis of optical data from melt ponds and bore holes.

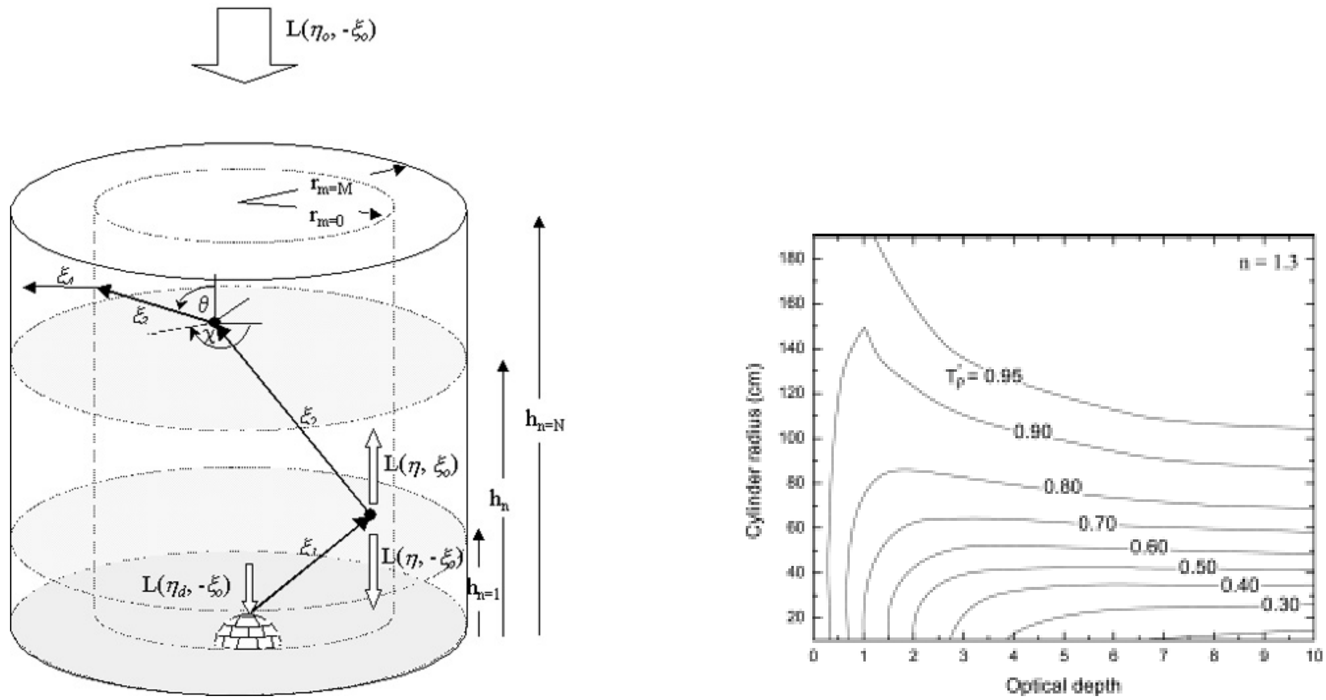


Figure 1. (a) Example of cylindrical sample domain for the 2-D Monte Carlo model. (b) Relative transmissivity (T_ρ^*) of a 50 cm high ice cylinder as a function of cylinder radius and optical depth.

A paper describing the formulation, development and testing of the model has been submitted to the *Journal of Geophysical Research* and is currently under review. The paper also presents results from recent studies that quantify differences between the apparent optical properties of sea ice cylinders and slabs. Figure 1(b) shows contours of transmission beneath the center of a 50 cm tall cylinder, relative to an infinite slab of the same thickness and material. If $T_\rho^* = 1$, the cylinder and the slab would be optically indistinguishable. As one might expect, cylinders with the smallest radius-to-height ratios produce the largest differences, particularly when the optical depths are large. Such differences arise because of light losses through the side of the cylinder. Interestingly, differences are nearly independent of optical depth once values exceed 3-5, indicating that these results can often provide a way to utilize quick, efficient 1-D calculations in the estimation of optical properties of a cylinder.

Radiative Transfer Beneath Melt Ponds

Surface melt ponds are a ubiquitous feature of summer sea ice in the Arctic [Fig 2(a)]. Due to thinner ice and low albedo, ponds are presumed to transmit substantial amounts of solar energy to the mixed

layer. The transmissivity of ponds has previously been measured by lowering instruments into the water through boreholes [Fig. 2(b)]. However, if the data were collected near the edge of the pond, effects from the optically thicker, surrounding bare ice could cause light attenuation by the ponds to be overestimated. A series of 2-D Monte Carlo simulations have been used to investigate this possibility. The model was centered on a melt pond surrounded by bare ice whose vertical structure was inferred from spectral albedo data collected during SHEBA [Fig. 3(a)]. The spatial distribution of transmitted radiation was then calculated within and beneath the ponded ice [Fig 3(b)] for different pond sizes and ice thicknesses. Results show that the radiation field beneath ponds <6 m in diameter is always affected by the surrounding ice, causing extinction coefficients to be overestimated. Even large ponds will yield overestimates if measurements are made within 2-3 m of the pond edge. For smaller ponds on thick

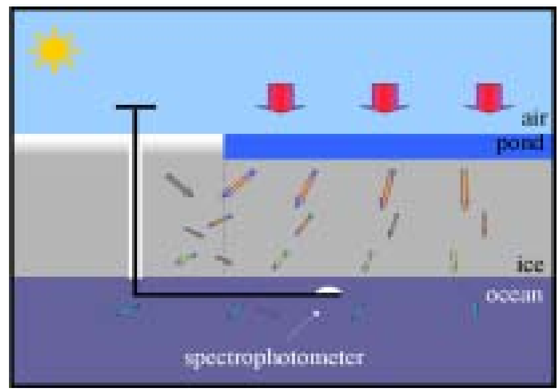
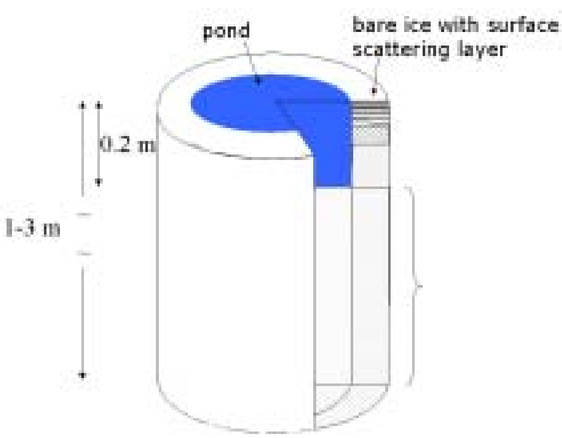


Figure 2. (a) Aerial photo of summer melt ponds on multiyear Arctic sea ice. (b) Diagram showing traditional method of measuring melt pond transmissivity by deploying instruments below the ice.



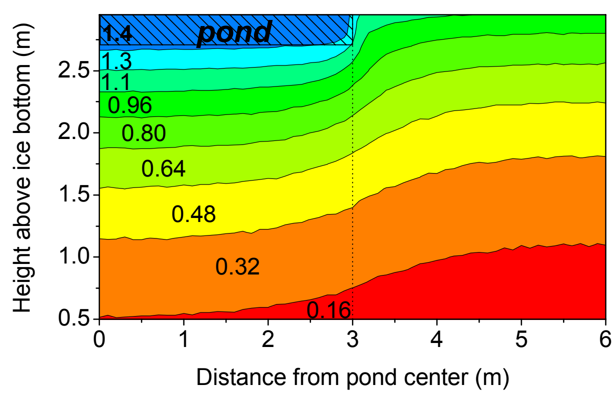


Figure 3. (a) Cylindrical Monte Carlo model geometry used in melt pond studies. (b) Predicted downwelling irradiance (normalized by incident value) beneath a 6 m diameter melt pond in 3 m ice.

ice, over 40% of the transmitted energy at 475 nm exits beneath the neighboring ice. It is clear that previous estimates of melt pond extinction coefficients need to re-examined in light of these findings. Results from this study were presented at a recent conference [Light, B. and G. A. Maykut, Light

transmission through ponded sea ice: A two-dimensional view, ARCSS All-Hands Workshop, Seattle, Februrary 2002]. A journal paper is in preparation.

Irradiance Profile Analysis

To complement underice transmission measurements, profiles of downwelling irradiance were collected within the ice at 20 cm intervals in vertical bore holes. Figures 4(a) and 4(b) show typical summer profiles beneath bare and ponded multiyear ice. The Monte Carlo model was used to examine the impact of the bore hole on the radiation field. It was found that the bore hole had little effect below about 30 cm. The profile data were then used to obtain averaged spectral extinction coefficients for the interior of different types of melting sea ice [Fig. 4(c)]. Surprisingly, the results showed that ponded ice attenuated light more strongly than the bare ice, perhaps because of greater vapor volume associated with higher brine volume. Even more surprisingly, extinction coefficients in the bare ice at SHEBA were only about half as large as previously reported values. This may be the primary reason why solar heating of the mixed layer was so much larger than expected. Specific implications of these findings will be studied in detail during the coming year.

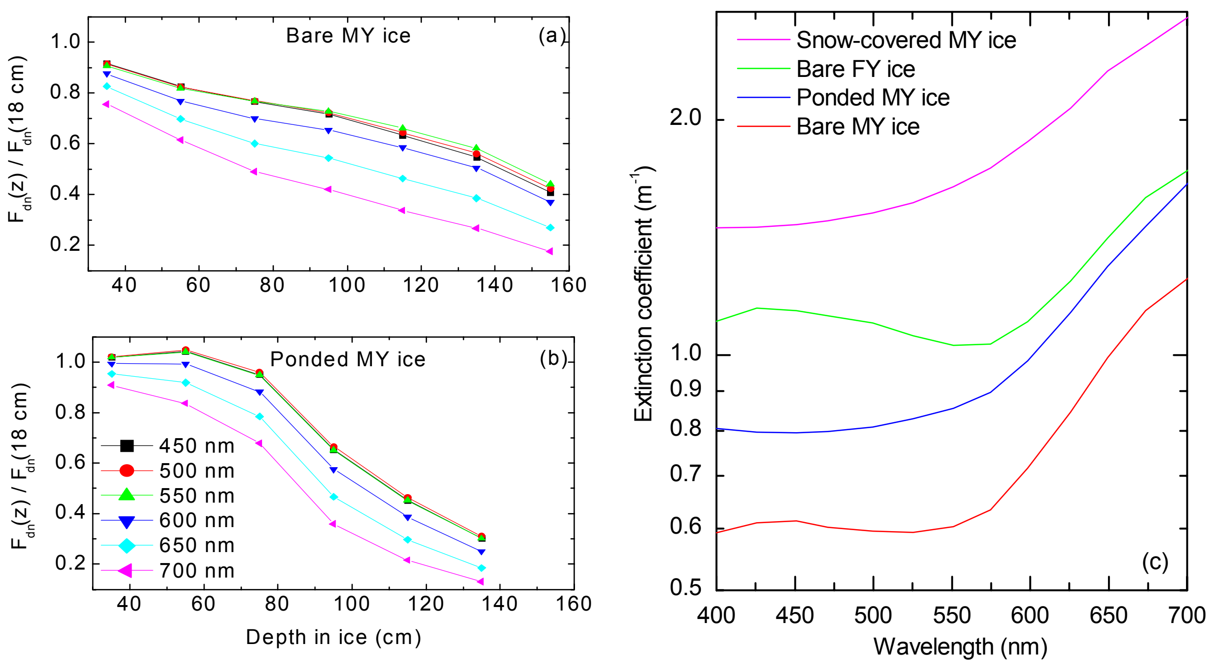


Figure 4. Profiles of relative irradiance beneath (a) bare ice and (b) ponded ice at various wavelengths (c) Averaged spectral extinction coefficients within different types of melting sea ice. Note the apparent chlorophyll signal in both the bare first-year and bare multiyear ice cases.

IMPACT/APPLICATIONS

Data obtained during the field effort provide the means to test theoretical models dealing with: (1) the transmission and absorption of light by the ice pack, (2) the role of leads and melt ponds in the regional heat and mass balance, and (3) the storage of solar heat in the water and its interaction with the ice cover. The laboratory and theoretical studies suggest that relatively simple parameterizations of radiative transfer in sea ice can be developed for large-scale modeling. We expect that these data

and modeling results will lead to an improved understanding of ice-albedo feedback processes that can be used to enhance the accuracy of predictions made by climate models and GCMs.

TRANSITIONS

Our heat and mass balance data collected at SHEBA are archived in the JOSS database and also placed on a CD-ROM which has been widely disseminated to the community. We expect that these data will be used in a variety of process and column modeling studies by ourselves and other groups. Results have been presented at numerous scientific conferences and written up in several journal papers.

RELATED PROJECTS

The work described above is part of a group project being carried out jointly with CRREL investigators funded under Contract N0001497MP30046. We are also working closely with other SHEBA Phase 3 investigators studying processes related to: (1) the recycling of solar energy absorbed by the ocean, (2) melt pond and ice cover evolution, and (3) energy exchange with the atmosphere. Data from this project will be used in modeling efforts funded under ONR, SCICEX, NASA-POLES, and NSF to calculate the ice thickness distribution and large-scale heat and mass fluxes.

PUBLICATIONS

Grenfell, T. C., B. Light, and M. Sturm, The spatial distribution and radiative effects of soot in the snow and sea ice during the SHEBA experiment, *J. Geophys. Res*, in press.

Perovich, D. K., T. C. Grenfell, B. Light, and P. V. Hobbs, The seasonal evolution of Arctic sea ice albedo, *J. Geophys. Res*, in press.

Light, B., G. A. Maykut and T. C. Grenfell, Effects of temperature on the microstructure of first-year sea ice, *J. Geophys. Res*., in press.

Perovich, D. K., H. Eicken, T. C. Grenfell, B. Light, J. Richter-Menge, W. Tucker, Thin and thinner: Ice mass balance measurements during SHEBA, *J. Geophys. Res.*, in press.

Eicken, H., T. C. Grenfell, D. K. Perovich, J. A. Richter-Menge, and K. Frey, Hydraulic controls of summer Arctic pack ice albedo, *J. Geophys. Res. Oceans*, in press.

Light, B., G. A. Maykut and T. C. Grenfell, A two-dimensional Monte Carlo model of radiative transfer in sea ice, *J. Geophys. Res. Oceans*, submitted, 2002.

Light, B., G. A. Maykut and T. C. Grenfell, A temperature-dependent, structural-optical model of first-year sea ice, *J. Geophys. Res. Oceans*, in preparation.

Light, B. and G. A. Maykut, Light transmission through ponded sea ice: A two-dimensional view, *J. Geophys. Res. Oceans*, in preparation.